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THE SOLAR SPECTRUM FROM 50 Å TO 400 Å

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Abstract: A scanning monochromator, mounted as a pointed experiment on OSO–1, has been used for observations of solar extreme ultraviolet radiation from 50 Å to 400 Å. The period of observation was sufficient to observe a slowly varying component having a period of approximately 27 days and correlating with solar activity. The enhancement of radiation during periods of activity was observed to vary from line to line in the spectrum, depending upon the origin of the line in the solar atmosphere. Data showed an increase in the He II Lyman-alpha (304 Å) flux, integrated over the entire solar disk, of 33 percent, during a period when the Zurich Provisional Relative Sunspot Number increased from zero (March 11, 1962) to a maximum of 94 (March 22, 1962). Enhancements of approximately a factor of four were observed for the 284 Å (Fe XV) and the 335 Å (Fe XVI) lines.

Резюме: Для наблюдений солнечной радиации в крайней части ультрафиолета от 50 Å до 400 Å использовался ориентированный сканирующий монохроматор, установленный на спутнике OSO-1. Период наблюдений был достаточен для того, чтобы наблюдать компоненту, медленно изменяющуюся с периодом приблизительно 27 дней и коррелирующую с солнечной активностью. Согласно наблюдениям увеличение радиации в периоды солнечной активности изменялось по спектру от линии к линии в зависимости от происхождения линии в солнечной атмосфере. Данные показали, что поток He II Лайман-альфа [304 Å], интегрированный по всему солнечному диску, увеличивается на 33% в течение периода, когда Цюрихское Условное Относительное Число Солнечных Пятен увеличивалось от нуля [11 марта 1962 г.] до максимума 94 [22 марта 1962 г.]. Увеличения примерно в четыре раза наблюдались для линий 284 Å [Fe XV] и 335 Å [Fe XVI]

1. Introduction

A grazing incidence spectrometer has been flown as a pointed experiment on OSO–1 to monitor the extreme ultraviolet spectrum of the sun. Over six thousand spectra were obtained at the rate of about 100 per day over a period of time from March through May 1962, corresponding to nearly three solar revolutions. Intermittent operation has subsequently provided spectra for a period of greater than one year. This paper presents, in a condensed form, the variations observed in three of the more reliably identified lines of the spectrum: 284 Å (Fe XV), 304 Å (He II) and 335 Å (Fe XVI).

The schedule of reduction of telemetry records was designed to provide a coarse look (several orbits per day) throughout the three month period of continuous observation. This approach is not suited for the detailed study of a particular event for which one must have continuous data over a period of hours. Therefore, transient phenomena on the sun are only now being studied as data reductions become more complete and the results will be presented in a future paper.

2. Description of spectrometer

During operation the spectrometer was pointed at the center of the solar disk within approximately two min of arc. In this orientation, radiation from the entire solar disk and inner corona passed directly through the entrance slit and struck a concave grating mounted in grazing incidence, the angle of incidence being 88°. The grating, an original ruled in a special glass by the Nobel Institute in Stockholm, had 576 lines per millimeter on a blank of one meter radius of curvature. The exit slit and detector were mounted on a carriage which was driven on a circular rail so that the exit slit scanned along the Rowland Circle, where the spectrum was focused, from 10–400 Å. The plane of the exit slit was approximately perpendicular to the diffracted ray at all positions along the track, thereby keeping the spectral passband nearly constant for all angles of diffraction. The 50 micron entrance and exit slits provided a spectral passband of 1.7 Å and permitted resolution of lines 0.85 Å apart. The detector was a windowless photomultiplier developed by the Bendix Corporation specifically for use in this spectrometer. A tungsten photocathode was chosen to minimize response to wavelengths above 1500 Å, and to reduce changes in sensitivity due to variations of the emission properties of the cathode.

3. Calibration of the spectrometer

The instrument calibration was performed by (1) exposing the entire spectrometer to a beam of monochromatic radiation of known intensity and (2) by evaluating the essential components of the spectrometer (grating, detector, etc.), and then computing the sensitivity of the instrument. The first method was used at 44 Å using a proportional counter for determining the source intensity. The second method was applied at longer wavelengths (80–400 Å).

In addition, a comparison was made of the solar fluxes obtained against the fluxes measured by Hall, Damon and Hinteregger [1] with a calibrated rocket instrument. The comparison could only be made in the region of overlap, 250 Å to 400 Å, and would be meaningful only if the solar radiation was the same. The 2800 Mc mean daily flux recorded by the National Research Council, Ottawa, Canada, was used as an independent estimate of solar flux to choose the satellite data for the comparison.

A best fit was made between these methods of obtaining a calibration which yielded values of 8.0×10^5 photons cm^{-2} $count^{-1}$ at 335 Å and 4.2×10^5 photon cm^{-2} $count^{-1}$ at 284 Å.

4. Presentation of data

Fig. 1 presents a typical scan obtained over the region of 170 Å to 400 Å. Several factors reduce the usable spectral range of the spectrometer from its nominal range of 10 Å to 400 Å. At wavelengths below 100 Å the decreasing sensitivity of the spectrometer combined with an increase in scattered light upon approaching the central image made it impossible to distinguish a reliable spectrum on a single scan. However, a combination of several scans, using cross-correlation techniques, has shown the apparent existence of a line emission spectrum in the region from 50 Å to 100 Å. At wavelengths above 342 Å the second order images of intense spectral lines observed in first order above 171 Å obscure a considerable amount of interesting data. This effect is illustrated in fig. 1 which indicates, by cross-

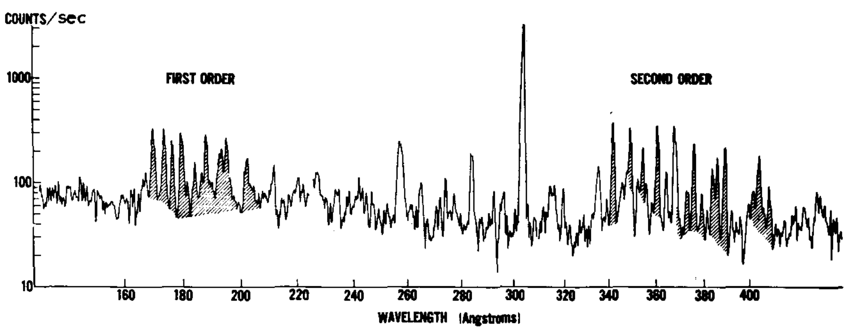

Fig. 1. Solar spectrum from 170 Å to 400 Å with second order line images indicated.

hatching, those first order lines which have strong second order counterparts in the recorded spectrum. These second order images were less prominent in earlier rocket results, leading to considerable dissimilarity between the rocket and satellite spectra above 342 Å (Neupert and Behring [2]). For these reasons the obviously usable range of the instrument can be considered to be from 170 Å to 340 Å, a range which can be extended, with special precautions, to cover the interval from 50 Å to 400 Å.

The brightest emission line in the region from 170 Å to 340 Å is the Lyman-alpha line of ionized helium at 304 Å. In addition, numerous other emission lines appear with combined flux comparable to, or somewhat greater than, that of the helium line. Resonance lines of heavy ions (Mg through Fe) are expected in this region, leading to attempts (Zirin, Hall and Hinteregger [3]), (Neupert and Behring [2]) to identify the more prominent features of the spectrum in terms of such lines. The difficulty of positive identification can be appreciated more if, for example, we realize that the resonance lines of all stages of ionization of iron from Fe XVI, with the exception of Fe XV, are expected in the small wavelength interval from 335 Å to 390 Å (Neupert and Behring [2]). The overlapping of these resonance multiplets combined with second order contamination of shorter wavelengths makes positive identification a formidable task. The resonance lines of Fe X through Fe XIV have not been identified in the extreme ultraviolet (EUV) spectrum although their intensity as predicted by Ivanov–Kholodny and Nikolsky [4] should permit their observation. Tousey [5], working with a spectrum having higher resolution, reports that no Fe XIV multiplet can be found in his record. Because of these difficulties, discussion will center around three of the more intense and more reliably identified lines of the spectrum, the Fe XV ($3s^2\,{}^1S_0$–$3s\,3p\,{}^1P_1^0$) line at 284 Å, the Fe XVI ($3s\,{}^2S_{1/2}$–$3p\,{}^2P^0_{3/2}$) line at 335 Å, and in addition, the He II ($1s\,{}^2S_{1/2}$–$2p\,{}^2P^0_{3/2,1/2}$) line at 304 Å. The location of these lines is indicated in fig. 2.

5. Time variations of the EUV spectrum

The months of March and April of 1962, were auspicious for a study of the solar EUV spectra in that observations could be made on both a quiescent and a disturbed solar atmosphere. During the second week in March the sun was especially quiet, the sunspot number being zero on March 11. As the month progressed the solar rotation carried several centers of activity across the visible hemisphere of the sun. Definite enhancements in the solar spectrum were associated with these centers of activity.

Fig. 2 presents two scans of the EUV spectrum which were obtained with a separation in time of approximately ten days. During the first of these observations (March 13) only one small region of activity was present on the solar disk. In spite of this low level of activity it is observed that the Fe XV and Fe XVI lines persist as two of the more prominent features of the spectrum. The second spectrum (March 23) was obtained while several large and well-developed centers of activity were present on the disk. Comparing these two spectra we observe that the emission lines have increased in intensity but not all by the same amount. The Fe XV and XVI lines, already prominent even in the absence of solar activity, have increased in intensity appreciably more than any other line observed with certainty in this spectral range. The He II line has also increased but by a lesser amount.

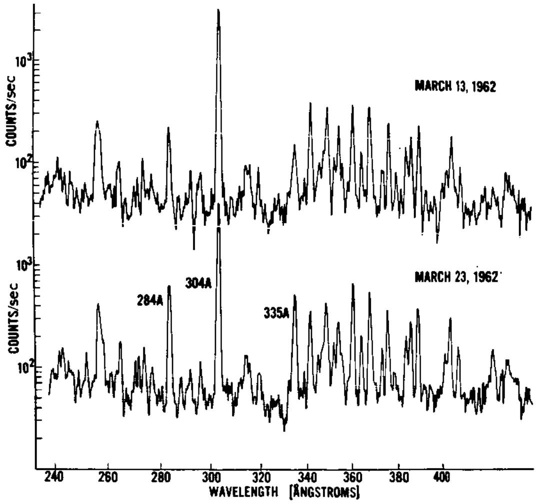

Fig. 2. Comparison of two spectral scans taken under different solar conditions:
March 13, 1962 – Solar disk showing one small active region.
March 23, 1962 – Solar disk having several well developed centers of activity.

Time variations of these three lines as observed for the first 1066 orbits of operation are given in fig. 3, in which each datum point represents the average of one orbit's observations (six to eight scans). Error bars indicating one standard deviation in the data are given for each wavelength. Also indicated are the times of appearance and disappearance of the major plage areas as cataloged by the McMath–Hulbert Observatory. The first increase in the counting rates above the "quiet sun" values is associated with the appearance of McMath Plage No. 6366 on the east limb on March 11. The slope of the He II curve is observed not to change appreciably on March 17 as several more prominent plages appear on the limb, although their appearance is obvious in the radio data. The counting rate for the He II (304 Å) line increases gradually to a maximum on March 23, after which it drops rather abruptly to an apparent plateau. This sudden drop cannot be unambiguously attributed to the disappearance of plage region 6366 on the west limb, for it follows quite directly after an unusual flare of importance 3 observed in plage region 6370 on March 22, for which data are not given in the figure. A gradual decline in readings is observed from March 29 to April 7. A similar enhancement, followed by a return to near pre-plage rates, occurred in April. Since the spectrometer did not carry an internal standard (e.g., radioactive source) it is impossible to state positively that its counting characteristics did not change over the period of observations. The consistent behavior of the data, however, as demonstrated in fig. 3, leads to the conclusion that no significant change in sensitivity occurred throughout the period of observation. (Subsequent analysis of real time data after one year in orbit supports this conclusion, even for the longer time interval.)

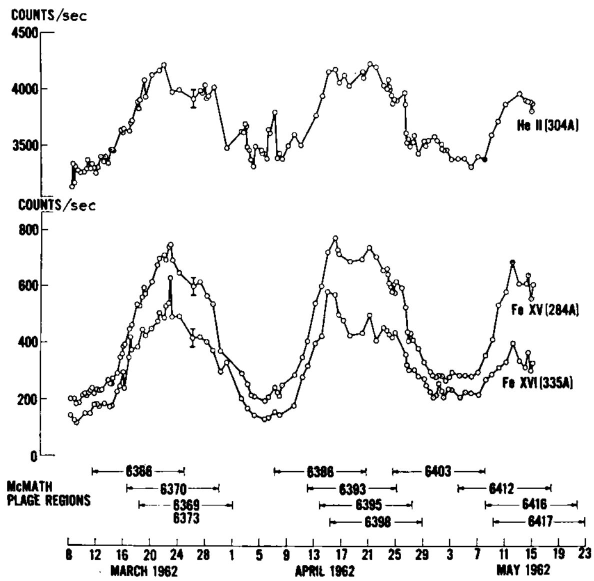

Fig. 3. OSO–1 data for three spectral lines compared with appearance and disappearance of major plage areas.

Also shown in the figure are the variations with solar activity of the coronal Fe XV (284 Å) and Fe XVI (335 Å) lines, the relative increases being considerably larger than for the He II (304 Å) line. A definite, although small, enhancement associated with the appearance of plage No. 6366 is observed in both the Fe XVI and Fe XV lines. The possibility exists that the coronal emissions appear slightly earlier as might be expected since the coronal emission must take place at greater heights than the calcium radiation. The most obvious increase in intensity of these lines is associated with the appearance in succession, of plage areas numbered 6370, 6369 and

6373 on March 17 through 19. The counting rates then increased gradually throughout this period indicating that the enhanced emission was not from a point source but rather from an extended volume having as its base an area at least as large as the underlying calcium plage. The disappearance of area 6366 on March 25 results in a slight decrease in counting rates, followed by a general decline from March 29 through April 3 as the other plage areas are carried off the visible hemisphere of the sun by the solar rotation.

Although the horizontal scale in fig. 3 is inadequate for the display of transient phenomena, at least one interesting event, associated with a flare of importance 3, on March 22, can be discerned. This flare was unusual in that the ionospheric effects produced by it were more nearly characteristic of a small (importance one) flare. An enhancement was observed at 304 Å (not plotted) simultaneously with the visible flare, but not at 335 Å or 284 Å. However, at the latter wavelengths a significant enhancement was noted one or two orbits after visible maximum. The peak point at 335 Å lies at eight standard deviations from the mean of the day's observations

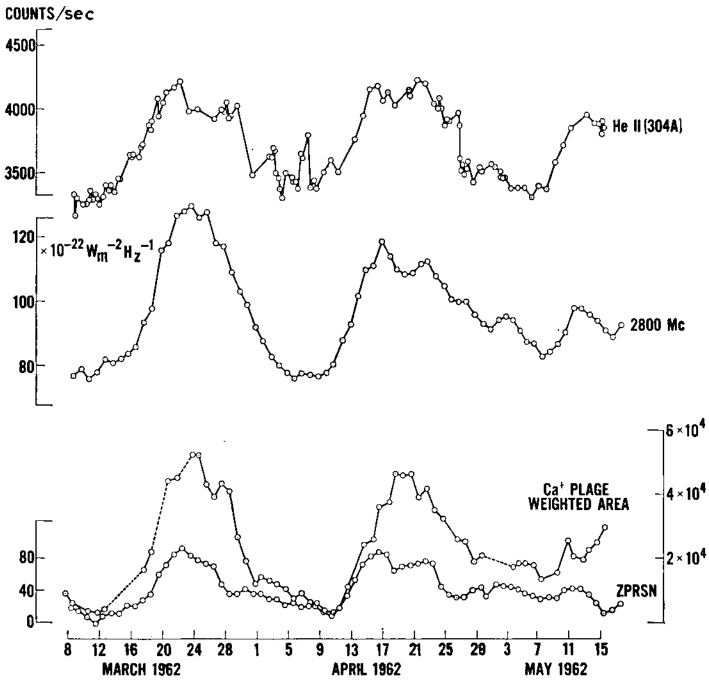

Fig. 4. Relationship of observed counting rates for the He II Lyman-alpha line to ground-based measurements of solar activity.

before the flare and represents a nearly certain change in the EUV flux. Further analysis of this event covering the major lines of the spectrum will be presented in a future paper.

The relationship of these observed counting rates to several ground-based measurements of solar activity is presented in figs. 4 and 6. In fig. 4 the He II radiation is compared with daily values of the solar flux at 2800 Mc, and with the Zurich Provisional Relative Sunspot Number (ZPRSN). Also shown is an estimate of the calcium plage area, each area being weighted by the estimated intensity of the area on a scale from 1 to 5. Values for

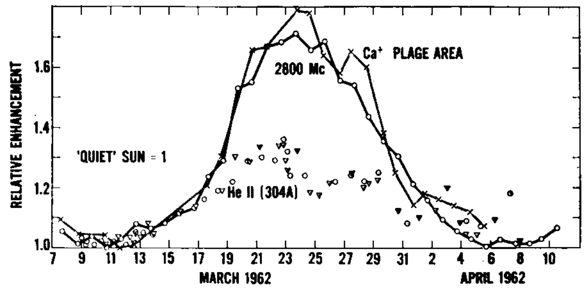

Fig. 5. Comparison of 304 Å data, normalized to a "quiet sun" value of one, with calcium plage data and 2800 Mc radio observations.

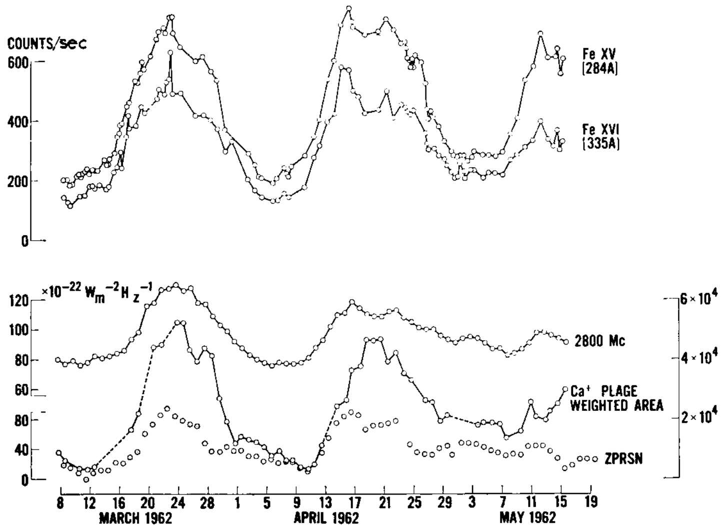

Fig. 6. Relationship of observed counting rates for the 284 Å and 335 Å lines to ground-based observations.

this computation were supplied by the McMath–Hulbert Observatory.

A more detailed comparison is made in fig. 5 in which the radio and He II fluxes have been adjusted by dividing each observation by the rate observed for the "quiet sun". In addition, the Ca^+ plage intensity has been adjusted to coincide with the 2800 Mc enhancement on March 21. This plot shows more clearly the close relationship which has been known for some time between the 2800 Mc radiation and the plage areas and also shows the divergences of the He II (304 Å) line from both of these. In fig. 6 the daily values of solar flux at 2800 Mc and the Zurich Provisional Relative Sunspot Number are compared with radiation due to the coronal lines of Fe XV (284 Å) and Fe XVI (335 Å). The estimated calcium plage intensity is also shown.

6. Discussion

The spectral lines chosen for presentation here were selected because they are reliably identified with particular ions, not because they convey more than any other line in the spectrum the changes in solar flux which occur with the appearance of plage areas. In terms of fractional changes in intensity, these three lines represent the extremes which have thus far been observed in the spectral region from 171 Å to 400 Å: only a few faint lines have smaller non-flare variations than the He II Lyman-alpha line, while no other lines have increases as great as those observed for 284 Å and 335 Å. A summary of the average increases in counting rates for the period from March 9 to 23, 1962, a period of increasing solar activity, is given in table 1. The increase, weighted by the intensity of each line, is computed for the range from 171 Å to 305 Å, using sixty reliably observed lines. The increase in the range from 305 Å to 400 Å can only be estimated because of the masking effect of second order images above 342 Å. The values given in table 1 are, of course, appropriate only for the particular interval in time for which they were computed.

TABLE 1

Increases in solar EUV spectrophotometer counting rates, March 9 to 23, 1962

Spectral range	Average counting rate increase
171 Å–228 Å	55 %
229 Å–300 Å	80 %
229 Å–305 Å	52 %
305 Å–400 Å	50 % (estimated)

The initial analysis of only three lines (He II 304 Å, Fe XV 284 Å, Fe XVI 335 Å) already indicates that the relative prominence of spectral lines may depend upon the age of the center of activity which is responsible for the increased radiation. As an example of this, one may observe (fig. 6) that the maximum emission in the Fe XV apparently occurs later in time than the maximum for the 2800-Mc radio flux or for the plage areas observed during March, April and May. In addition to such a slowly changing effect, one may note that localized perturbations appear (March 7–9 and April 16–17) for which the relative increases are considerably different for the helium and the iron lines. It appears that in these instances we are observing phenomena localized at particular levels in the solar atmosphere.

7. Conclusions

Observations of the solar spectrum between 170 Å and 340 Å have been made over a time interval corresponding to approximately three solar rotations. The observations have shown:

(1) That the He II (304 Å) emission is enhanced by a factor of about 33 % during a period when the Zurich Provisional Relative Sunspot Number increased from zero to a maximum of 94 and the 2800-Mc flux varied from approximately 76 to 125×10^{-22} Wm^{-2} Hz^{-1}.

(2) The Fe XV (284 Å) and Fe XVI (335 Å) coronal lines were enhanced during the same period by a factor of approximately four.

(3) The enhancement of He II (304 Å) and Fe XV (284 Å) and Fe XVI (335 Å) due to plage activity was larger than enhancements due to flares that occurred during the three-month interval of the observations.

(4) The variations in intensity of the He II (304 Å), Fe XV (284 Å) and Fe XVI (335 Å) represent the extremes observed. If one averages sixty of the reliably observed lines between 171 Å and 342 Å the enhancement is between 50 % and 80 % for the time interval March 9 to 23.

(5) Although there appears to be a gross correlation between solar activity indices (such as 2800 Mc flux) and the He II, Fe XV and Fe XVI fluxes, there are indications that the relative prominence of the spectral lines may depend upon the age of the center of activity.

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